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The work performed under this contract may be broken up into three parts, each headed by a different PI. The three parts and respective PI's are: (1) Modification of FEM code for inclusion of large strain plasticity (X. Deng), (2) Development of a computer based crack closure measurement system (M. A. Sutton), and (3) Database development for computer based structural life prediction (A. P. Reynolds). Brief synopses of the work performed under each section follow. Complete, detailed reports have been/will be submitted to appropriate NASA technical contacts.

## Development of FEM Code

Under the sponsorship of Dr. James C. Newman, Jr. at NASA LaRC, Dr. Deng was asked to develop a code to assess the effects of large rotation and large deformation on crack tip opening displacement for specific specimen geometries, the Arcan and M(T) specimens. To perform this work, Dr. Deng made substantial modifications to his existing codes and developed an Updated Lagrangian finite element code for studying two-dimensional problems in elastic-plastic solids. The code was validated using known solutions to large-scale deformation problems and then applied to the Arcan and M(T) specimens to determine if large-scale rotations were important. The work was successfully completed ahead of schedule and met all requirements from Dr. Newman. Dr. Deng and Dr. Newman published a NASA Technical Memorandum outlining the development and application of the new code, which is designated ZIP2DL.

## Development of a computer based crack closure measurement system

An accurate and relatively simple methodology for estimating crack closure loads at user-specified positions relative to the moving crack tip during the entire fatigue crack growth process has been developed. The methodology has three distinct components which are (a) an imaging system having adequate magnification with minimal distortion, (b) a simple, Windows-based comoputer program for image acquisition and image analysis and (c) techniques for obtaining a random, high contrast pattern on the specimen's surface.

To meet the imaging requirements, a far-field microscope objective capable of high magnifications was employed to image regions on the order of 0.5 mm by 0.5 mm in size near the crack tip. To meet the requirements of a user-friendly system, a state-of-the-art, Windows-based, PC data-acquisition interface was developed. Using the interface, images are acquired automatically during a loading/unloading cycle and stored digitally. Image analysis is performed to rapidly obtain the crack opening displacement as a function of load; this data is used to estimate the crack closure load. In addition, two methodologies for applying a random, high-contrast pattern with average sizes of 4 to 20 microns were developed. The first method uses 11 micron filter paper and a low-pressure compressed air supply to apply small particles of xerox toner powder to the surface of the specimen. The second method uses contact lithography to achieve a random pattern with smaller feature sizes, on the order of 2 to 8 microns.

Baseline tests of the overall system have demonstrated that it is both easy to use and accurate. Specifically, (a) it has been demonstrated that the PC Interface can acquire images automatically while the loading frame is cycling at 0.01 Hertz and (b) the crack tip opening displacement data has been shown to have errors on the order of 0.05 pixels in terms of the standard deviation for the xerox toner powder patterns, corresponding to 27 nanometers for the magnification used.

**Database development for computer based structural life prediction**

The goal of the above referenced program was to enhance the ability of the NASGRO fatigue life prediction program in the area of environmental effects on fatigue crack growth. The alloy system chosen for examination was A286, an iron-based superalloy. Frequency effects on fatigue crack growth rate were examined as functions of $K_{max}$, $\Delta K$, and temperature. Attempts were then made to develop equations which could be used to predict fatigue crack growth rates in this system from a limited fatigue crack growth data set. It was hoped that the form of successful predictive equations would allow extraction of information regarding physical mechanisms of fatigue crack growth in A286 at elevated temperatures.

The bulk of the effort was devoted to developing predictions based on a linear superposition assumption. That is, it was assumed that contributions to fatigue crack growth rates due to mechanical fatigue, monotonic load crack growth (like SCC) and corrosion fatigue could be summed to produce the overall da/dN as shown in the equation:

$$\frac{da}{dN_{total}} = \frac{da}{dN_{mechanical}} + \frac{1}{f}\frac{da}{dt_{SCC}} + \frac{da}{dN_{CF}}.$$

Development of appropriate functionalities of the terms on the RHS of the above equation with respect to frequency, $\Delta K$ and R requires generation of significant quantities of data and optimization of curve fits to those data. To date, an extensive data base of fatigue crack growth rate behavior has been generated. In particular, temperatures between 427°C and 600°C have been investigated. Frequency effects have been examined for loading frequencies between 0.01 and 10 Hz. These effects have been examined for numerous levels of $K_{max}$ and $\Delta K$. Currently, appropriate data fitting equations are being developed in conjunction with researchers at Rocketdyne.